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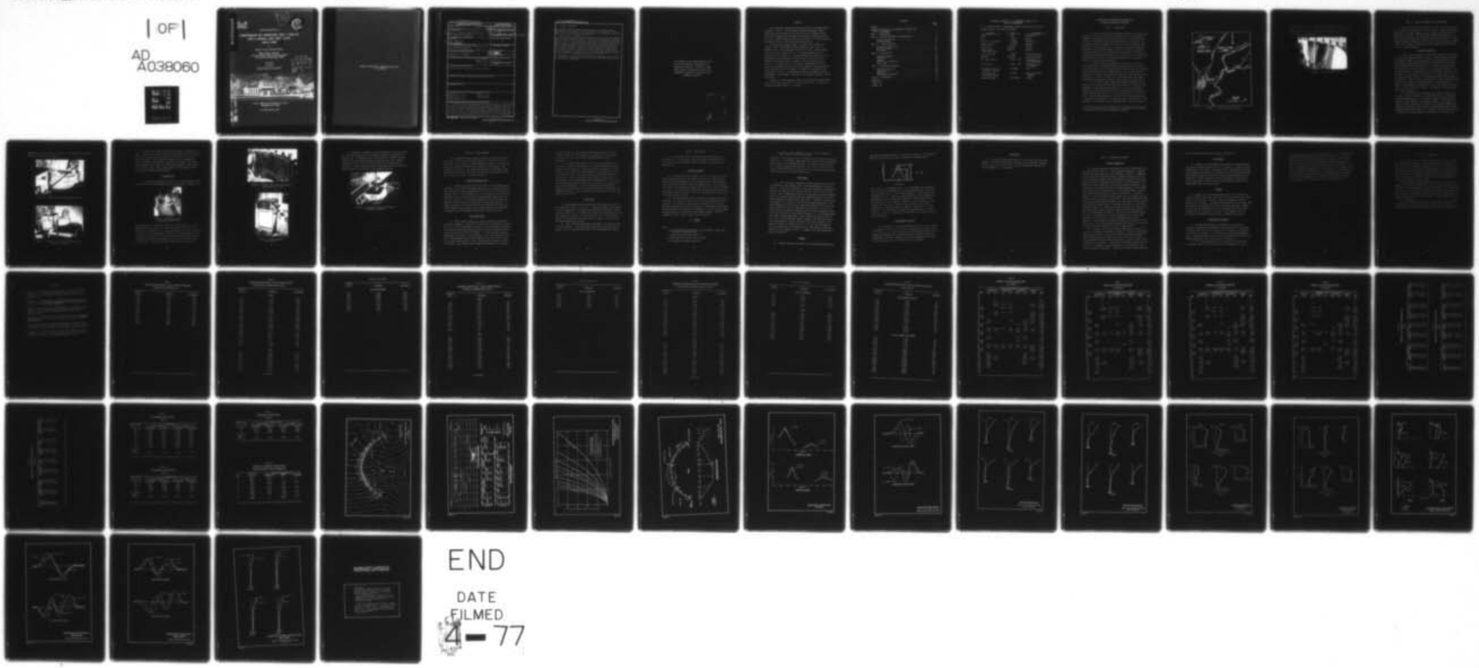

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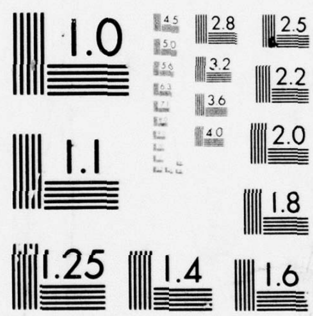

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TECHNICAL REPORT N-77-1

COMPARISON OF VIBRATION TEST RESULTS FOR A MODEL AND PROTOTYPE ARCH DAM

by

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P. O. Box 631, Vicksburg, Miss. 39180

March 1977
Final Report

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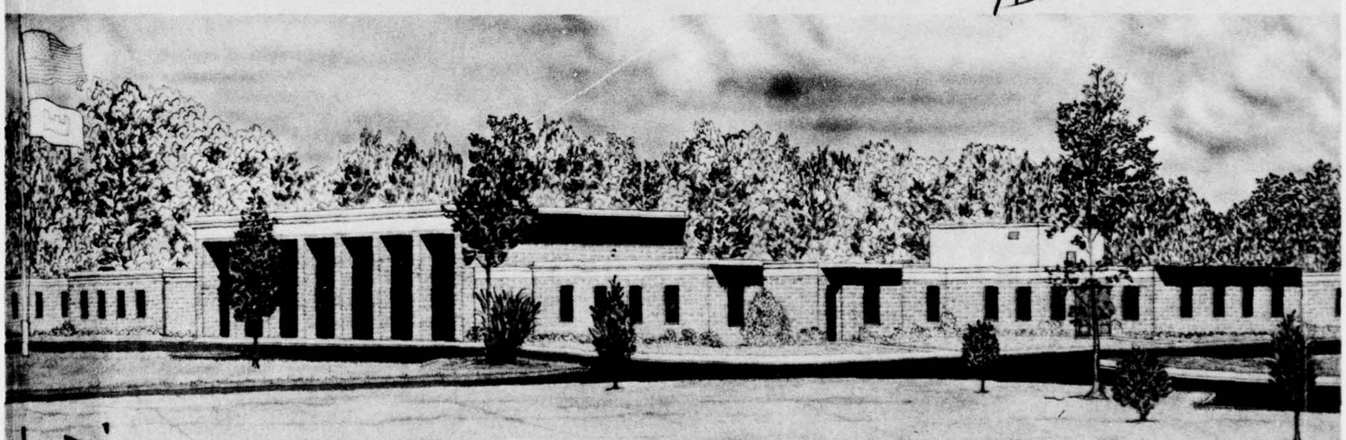

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Vibration tests were conducted on both the prototype and a 1:24-scale model of the North Fork Dam, a double curvature arch dam, to determine natural frequencies, mode shapes, damping ratios, and hydrodynamic pressures. Two vibrators mounted on the crest of the dam were used as input excitation sources for both series of tests. Electromagnetic shakers capable of a 40-lb output were used in the model tests, while counterrotating, eccentric mass exciters capable of a 5000-lb output were employed for the prototype. Velocities (Continued)
next page

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20. ABSTRACT (Continued).

were measured along the crest and downstream face of the model, whereas accelerations were measured in the same locations on the prototype. Measurements in both curves were taken at the dam-reservoir interface while the structures were excited at resonant frequencies.

Variations in the measured natural frequencies for the model and prototype ranged from approximately 3 percent for the third and fourth modes to approximately 25 percent in the second mode. Comparisons of corresponding mode shapes were quite good. A linear three-dimensional finite element code, SAP, was also used to compute mode shapes and natural frequencies for the dam. This analytical calculation was very accurate, as the variation in prototype and predicted natural frequencies ranged from less than 1 percent for modes 3 and 4 to 11.6 percent for mode 2. The finite element analysis also indicated the first natural frequency (compression mode) to be very close to the first bending modal frequency. In both model and prototype tests these two modes could not be separated, and the compression mode was not excited.

Damping in both model and prototype ranged from approximately 2 to 5 percent of critical. These values are consistent with structural damping values for these types of structures.

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PREFACE

This study was conducted during the period July 1973-May 1976 by personnel of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers (OCE). The work was funded under the Material Interaction Program, Work Unit No. 31210, "Dynamic Response Studies on Arch Dams." Mr. Lucian Guthrie, Engineering Division, OCE, was the Technical Monitor.

This work was conducted under the supervision of Messrs. W. J. Flathau, Chief of the Weapons Effects Laboratory (WEL), and J. T. Ballard, Chief of the Structures Division (SD), WEL. Various phases of the study were directed by Dr. J. P. Balsara and Messrs. R. D. Crowson and C. D. Norman, SD. The experimental work conducted on the prototype dam was performed by the University of California (UC), Berkeley, California, under a contract to WES and directed by Professor R. W. Clough and Mr. R. M. Stephen. Acknowledged for their efforts in assisting with the tests and arranging for preparatory work at the dam site are Mr. R. Parsons, UC; Messrs. Bill Heyenbruch and Larry Smith of the U. S. Army Engineer District, Sacramento; and dam caretaker Mr. Ray Wardrobe. This report was prepared by Messrs. Crowson and Norman.

Directors of WES during the conduct of this study and the preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
pounds (force)	4.448222	newtons
kips (force)	4448.222	newtons
pounds (force) per square inch	6894.757	pascals
feet per second	0.3048	metres per second
kip-feet	1355.818	kilonewton-metres
μin. per kip-foot	1.874×10^{-8}	millimetres per kilonewton-metre
μin. per kip	5.710×10^{-6}	millimetres per kilonewton
horsepower (550 foot-pounds per second)	745.6999	watts
386.4 inches per second per second	9.81456	metres per second squared
degrees (angular)	0.01745329	radians

COMPARISON OF VIBRATION TEST RESULTS FOR A MODEL AND PROTOTYPE ARCH DAM

PART I: INTRODUCTION

1. In order to develop better design procedures for concrete dams subjected to earthquake forces, an understanding of the significant parameters that influence the dynamic properties of such structures is necessary. Assumptions regarding geometry, boundary conditions, and interaction with the foundation and reservoir can significantly affect earthquake response calculations. Vibration tests provide a means of experimentally determining dynamic properties of dams and evaluating the various parameters that influence these properties. The experimentally determined dynamic properties can then be used to verify modern computational procedures currently being developed for the dynamic analysis of large concrete structures.

2. The North Fork Dam program was initiated in an effort to effectively study the dynamic response characteristics of a concrete arch dam through the use of model and prototype vibration tests together with three-dimensional (3-D) linear dynamic finite element analysis. Results of the model tests and analysis have previously been reported in References 1, 2, and 3. Results of the prototype tests and analysis together with comparisons with model test results are reported herein.

3. The North Fork Dam, located near Auburn, California, on the North Fork of the American River (Figure 1), was built in 1939 to trap sediments from upstream mining operations. It is a constant-angle arch with a maximum height of 155 ft,* a crest length of 620 ft, and a crown thickness that varies from 22 ft at the base to 6.8 ft at the crest. The overflow spillway is a section 200 ft long near the center of the dam and is depressed 3 ft below the normal crest elevation. The reservoir is very narrow, having a maximum width of about 700 ft and a

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

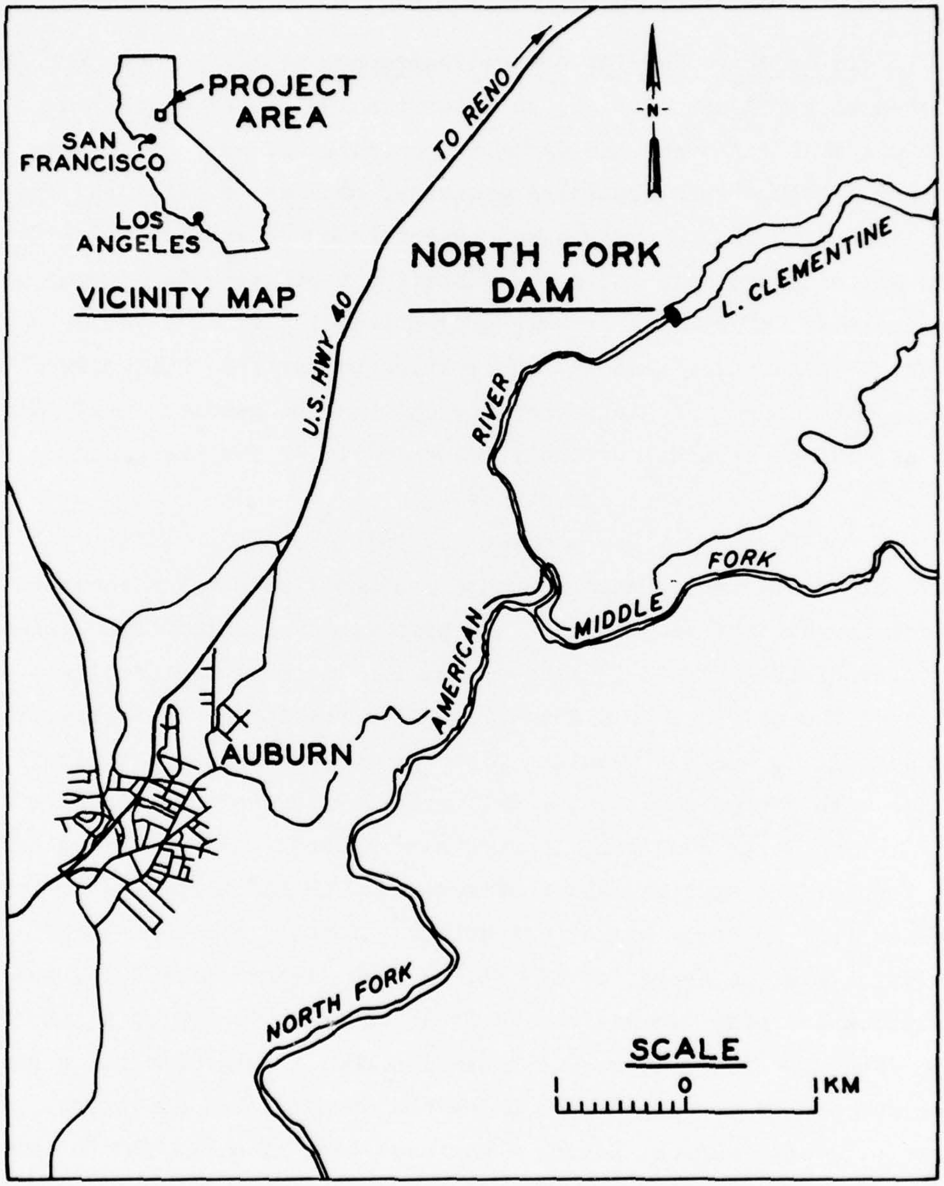


Figure 1. Location of North Fork Dam

length of about 5 miles. Completion of the Auburn Dam 5 miles downstream will cause the North Fork Dam to be completely inundated. The North Fork Dam is shown in Figure 2 with plan and profile shown in Plates 1 and 2, respectively.

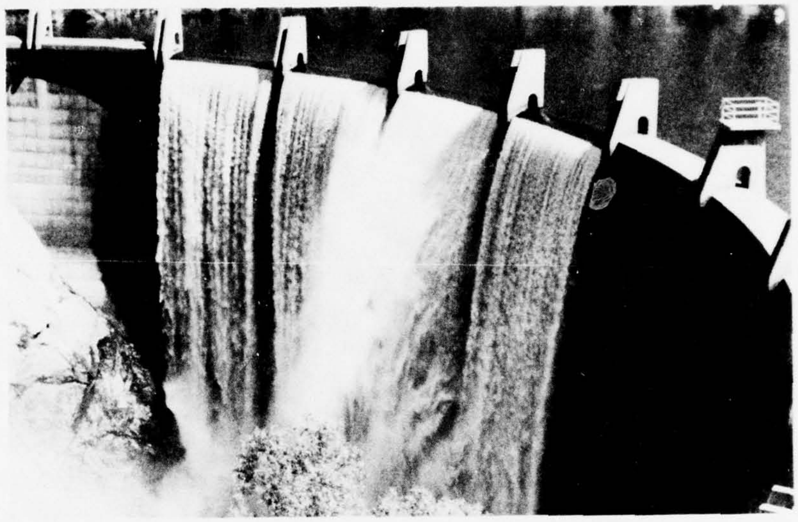


Figure 2. North Fork Dam

PART II: TESTING EQUIPMENT FOR PROTOTYPE DAM

4. Vibration tests were performed on the North Fork Dam to determine the dynamic characteristics of the structure. Natural frequencies, mode shapes, structural damping, and hydrodynamic pressures were the parameters of interest. The tests were conducted by personnel of the University of California (UC), Berkeley, California, and the U. S. Army Engineer Waterways Experiment Station (WES) during the period September-October 1974. Types of equipment used during the tests are described in the following paragraphs.

Vibration Generators

5. Two vibration generators, mounted on either side of the spillway, were used throughout the test series. These vibrators, described in References 4 and 5, were developed at the California Institute of Technology, Pasadena, California, under the supervision of the Earthquake Engineering Research Institute for the Office of Architecture and Construction, State of California. A horizontal sinusoidal force is generated by two counterrotating eccentric weights contained in baskets which revolve about a vertical shaft. The force output is controlled by varying the weight in each rotating basket and the speed of the operation. Plate 3, taken from Reference 5, gives complete response curves of the vibrator for various weights. The maximum force of 5000 lb is obtainable at frequencies of 2.5-9.7 Hz, while at the lower limit of 0.5 Hz, the force is 200 lb. The vibrator is shown attached to the dam in Figure 3.

6. The electric drive and speed control system consists of a 1-1/2-hp d-c drive motor used in conjunction with a servo-controlled electronic amplidyne unit. A tachometer, driven by the d-c motor, supplies a speed signal to an electronic counter. This signal, 300 times the basket frequency, is compared with a reference signal; the difference provides an input signal to the amplidyne amplifier, which adjusts the drive motor speed. The frequency control of this system is 0.1 percent, and stable operation is possible for structures with

damping as low as 0.5 percent of critical. The vibrator and electronic control unit are shown in Figure 4.

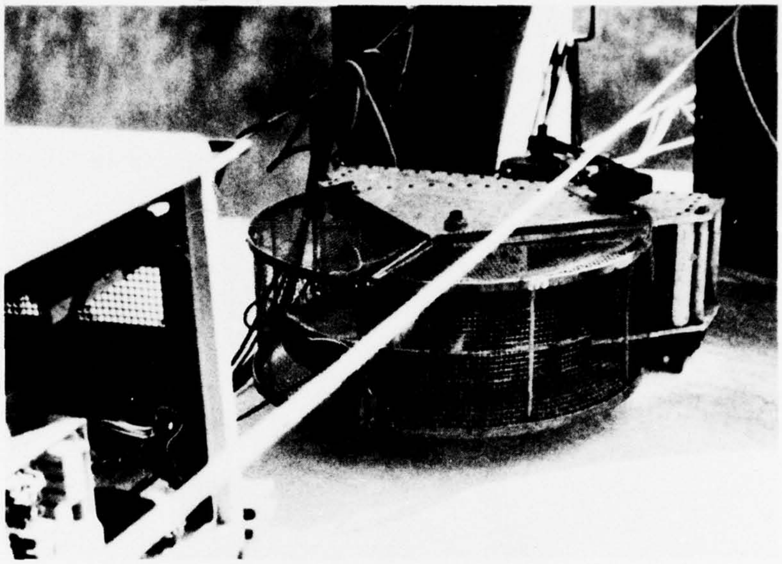


Figure 3. Vibrator used to excite prototype dam

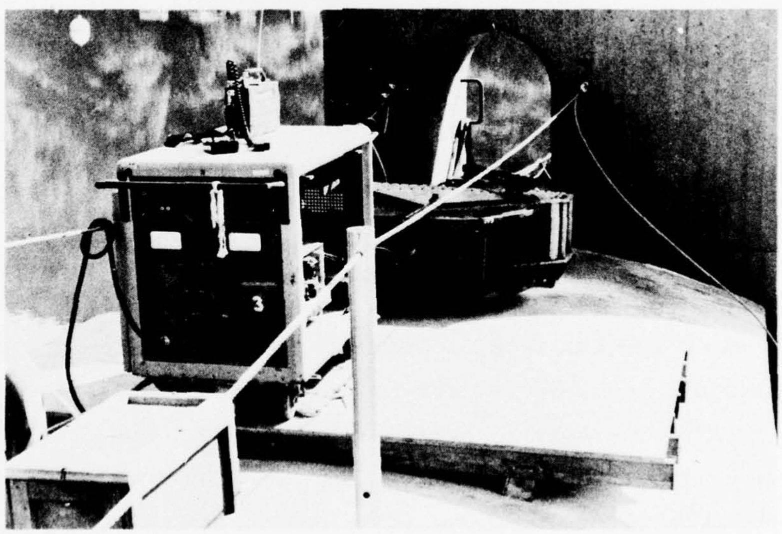


Figure 4. Vibrator and electronic control console in place on dam crest

7. Two or more vibrators may be run in phase or 180 deg out of phase. A master control unit drives a selsyn transmitter from the drive motor, and a selsyn receiver is attached to the drive motor of each separate vibrator. Any difference in angular position between the master and slave units produces a position error signal. This signal is then applied to the input of the amplidyne amplifier, which adjusts the slave unit speed. Thus, synchronization is maintained by both a velocity and a position control system.

Instrumentation

8. Both radial and tangential motion of the dam was measured with Statham Model A4 accelerometers, shown on the dam crest in Figure 5 and

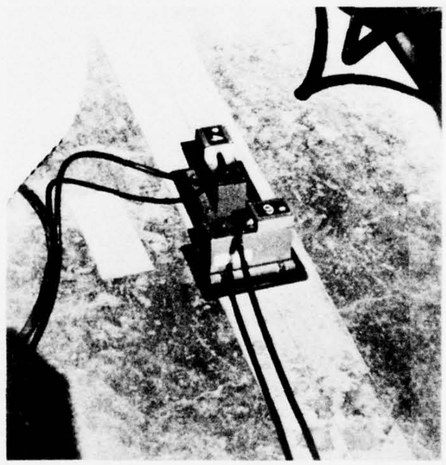


Figure 5. Accelerometers used to measure motion of dam

being mounted on the dam face in Figure 6. These transducers use an unbonded, balanced, fully active strain-gage bridge, and have a natural frequency of approximately 15 Hz and a damping ratio of 0.7 $\pm$ 0.1 percent of critical at room temperature. Signals from the accelerometers were amplified by a Validyne CD 90 Amplifier System before being recorded by a Honeywell 1858 Graphic Data Acquisition System on 8-in.-wide light-sensitive paper. The amplifier and recorder are shown in Figure 7.

Figure 6. Workman installing accelerometer on downstream face of dam

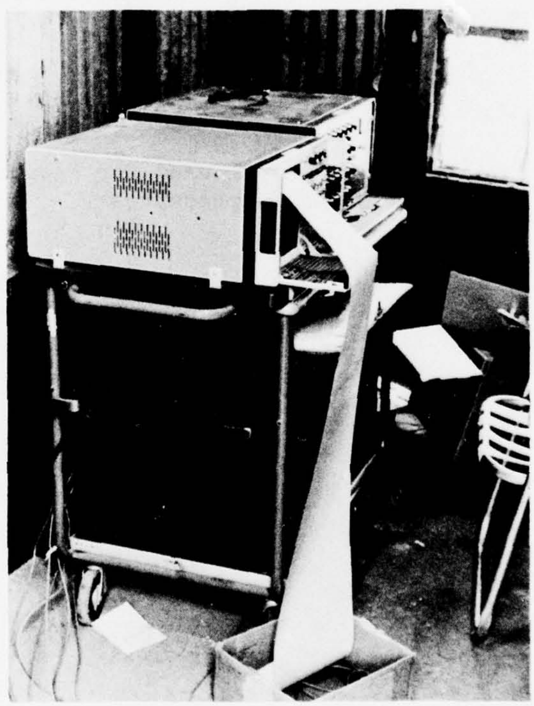


Figure 7. Signal amplifier and recorder

9. Hydrodynamic pressures on the upstream face of the dam, caused by the forced vibrations, were measured by lowering a transducer into the reservoir. The pressure cell, Kistler Model No. 206M111, shown in Figure 8, does not detect hydrostatic pressure, has a flat frequency response from 1 to 1000 Hz, and has a sensitivity of approximately 100 mv/psi. Signals from the transducer were amplified by a Burr-Brown 3088/16 amplifier and recorded on the Honeywell recorder.

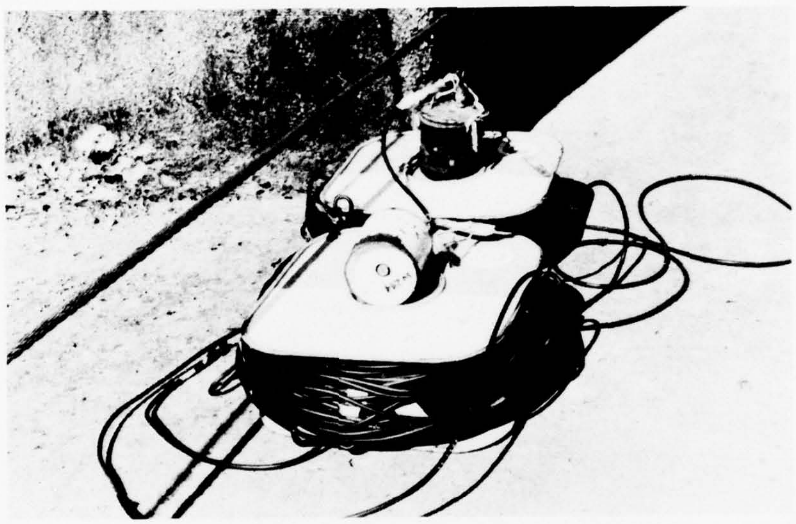


Figure 8. Pressure cell used for measuring hydrodynamic pressures

PART III: TESTS CONDUCTED

10. Instrumentation and vibrator locations on the dam are shown in Plate 4. The master vibrator was placed 4 ft from sta 6 and the slave unit 4 ft from sta 10. Steel frames were secured to the dam crest by six 1-in.-diam, 12-in.-long bolts anchored in the concrete. The vibrators were bolted to the frames and oriented so that radial forces were applied to the dam. The vibrators were run both in phase and 180 deg out of phase in order to excite all modes.

Resonant Frequency Tests

11. Frequency sweep tests were conducted with accelerometers located at sta 6, 8, and 10 measuring radial motion. The vibrator speeds were increased in small increments from 3.5 to 9.25 Hz with acceleration readings taken at each frequency step. For each reading, the vibration response was given sufficient time to become steady state before the data were recorded. Plots showing acceleration versus frequency were made and resonant frequencies determined for each peak amplitude. For higher resolution, tests were rerun with the frequency interval steps near resonance taken as small as the vibrator speed control permitted. In regions away from resonance the steps were relatively large.

Mode Shape Tests

12. After resonant frequencies had been identified, mode shape tests were conducted. Shapes of the crest and of the cantilever sections at sta 6, 8, and 10 were found for modes 2-5. Measurements to determine the deflected crest shapes were made in the radial and tangential directions at each station (50-ft intervals). For the cantilever sections, measurements were made at 45-ft intervals. Due to an insufficient number of accelerometers and recorder channels, data at all points could not be taken simultaneously. After recording the response of a number of locations, the vibrators were stopped, accelerometers were shifted

to new positions, and the structure was again excited at the same resonant frequency. This procedure was repeated until the response at all points on the dam for each resonant frequency had been determined.

13. In using roving transducers to obtain mode shape data, a reference point must be maintained. All other measurements are thus relative to the reference. Such relative data are necessary so that the amplitude and phase of each measurement can be adjusted to a constant modal amplitude. Both static and cross calibration procedures were employed. Static calibration was performed by placing each accelerometer on an inclined plane which corresponded to a 0.2-g input. The amplifier gain was then turned up to a sensitivity of 0.001 g per inch of chart amplitude. A cross calibration was accomplished by placing all accelerometers at sta 6 and recording each response to the common input motion. These calibrations were performed twice each day, before and after tests.

Other Tests

14. Hydrodynamic pressure measurements were taken for each resonant frequency at sta 6, 8, and 10. A pressure transducer was lowered down the upstream face of the dam, and dynamic pressures were recorded at various elevations. The transducer, enclosed in a watertight housing, was attached to a length of 1/4-in.-diam rope. Due to the upstream curvature of the dam, as the transducer was lowered, contact with the dam was maintained at all times.

15. Sonic vibration measurements were made at two locations near the south abutment. Two readings were taken across the crest and two across a pier to determine the seismic velocity through the concrete.

PART IV: TEST RESULTS

16. All data were reduced from the raw recorded signals by personnel of UC. These data, as well as a general description of the test procedure, were furnished to WES in the form of a data report, Reference 6.

Frequency Response

17. Accelerometers were located at sta 6, 8, and 10 for the resonant frequency searches. The output records at sta 8 were used in locating resonant frequencies for the in-phase tests, and the records at sta 6 and 10 were used for the out-of-phase tests. For the initial test series, the frequency was slowly varied from 3.5 Hz up to a maximum of 9.25 Hz. For these and all other tests, the vibrators were run with either empty baskets or load S1 (Plate 3), resulting in an output force of 1000-5000 lb per vibrator.

18. After the general range of the resonant frequencies had been identified in the initial tests, a more detailed frequency search was conducted. The results of these tests are presented in Plate 5, as frequency response curves, and in Tables 1-5. The harmonic acceleration data recorded during the tests were normalized to account for the changing force, which is a function of the frequency squared. The data presented in Plate 5 were obtained from the relation:

$$A = \frac{ag}{4\pi^2 f^2 F}$$

where

- A = peak displacement amplitude, in./kip, symmetric modes, and in./kip-ft, asymmetric modes
- a = peak acceleration amplitude, g's
- g = gravitational constant, 386.4 in./sec^2
- f = excitation frequency, cycles/sec

F = excitation force, symmetric modes, or couple, asymmetric modes, kips or kip-ft, respectively

Magnitudes of the input forces were computed from the relations given in Reference 5. The response curves shown are best-fit curves through data points obtained from several test runs. From these curves, the first four resonant frequencies excited were 5.75, 6.30, 7.54, and 8.40 Hz. Plate 5 shows data from sta 6 for the 5.75- and 7.54-Hz curves and data from sta 8 for the 6.30- and 8.40-Hz curves.

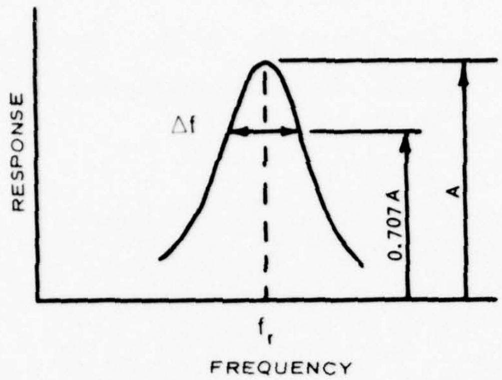
Mode Shapes

19. Once the natural frequencies had been identified, tests were run dwelling at each frequency while recording acceleration at every station. It should be noted that the resonant frequencies determined at the test site and used for the dwell tests were 5.80, 6.30, 7.62, and 8.53 Hz. These frequencies, obtained from acceleration versus frequency plots, are slightly different from those determined using the more detailed normalized response curves from Plate 5. However, the difference in frequency is too slight to alter the mode shapes appreciably. The shapes determined from the dwell tests are presented in Plate 6 for the crest and Plates 7 and 8 for cantilever sections at sta 6, 8, and 10. These shapes are normalized, showing only the relative response of each position on the dam for a particular frequency, i.e., the station having the largest response amplitude at each frequency was given a value of +1.0. Due to an insufficient number of gages to map the entire structure simultaneously, several tests were run at each frequency as the gages were moved to different locations. For all tests the gage at sta 6 was maintained as a reference and all other data were adjusted relative to the readings at sta 6. A summary of the mode shape data is given in Tables 6-12.

Damping

20. Damping capacities are shown on the frequency response curves

and varied from approximately 2 to 5 percent of critical. The bandwidth method, as shown below, was used to determine the damping values:



$$\frac{C}{C_{cr}} = \frac{\Delta f}{2f_r}$$

where C/C_{cr} is the damping ratio, Δf the difference in frequency of the two points on a resonance curve with amplitudes 0.707 of the resonant amplitude, and f_r the resonant frequency. Theoretically, the damping ratio C/C_{cr} relation is applicable only to the displacement-resonance curve of a linear, single-degree-of-freedom system with a small amount of viscous damping. However, it has been widely used for systems other than that for which it was derived, and has become accepted as a reasonable measure of damping. Furthermore, for large structures it is sufficient to express the damping ratio in a range, such as 1-2 percent, 2-5 percent, 5-10 percent, etc., rather than as an exact percentage.

Hydrodynamic Pressures

21. Hydrodynamic pressure measurements, made at sta 6, 8, and 10, are presented in Plates 9, 10, and 11, as pressure versus depth curves, and in Tables 13-15. These measurements were made while dwelling at the resonant frequencies with a pressure transducer lowered down the upstream face of the dam. Readings could not be obtained at full depth due to approximately 30 ft of buildup of silt and debris.

Sonic Tests

22. Sonoscope readings were taken at two locations near the south abutment. Two measurements made at the sta 2 tower indicated an average seismic velocity of 15,300 ft/sec. From two measurements through the crest the average was 11,500 ft/sec.

PART V: DISCUSSION OF RESULTS

Natural Frequencies

23. Natural frequencies determined for a 3-D finite element analysis and vibration tests of a 1/24-scale model (Reference 3) together with the prototype test results are presented in Table 16. Comparison of these results indicates variations in measured frequencies for the model and prototype ranging from approximately 3 percent for the third and fourth modes to approximately 25 percent in the second mode. The reasons for these variations in model and prototype frequencies can be attributed to the combined effects of several parameters. These parameters include accurate representation of prototype geometry, boundary conditions, material properties, and test procedures. Of specific interest is the fact that the aeration piers on the prototype dam crest (Figure 2) were not provided on the model. Also, the respective weights of the model and prototype vibrators do not correspond with those values that would be obtained by use of the model scale factor. Since these eccentric masses (i.e., aeration piers and vibrators) are located on the dam crest, their effects on natural frequencies could be significant. Also, the extensional mode (Mode 1, Table 16) was not detected during the model or prototype test but was indicated by the finite element analysis to be very close to the first asymmetric mode (Mode 2, Table 16). Such clustering of modes could present problems in the stability of the first measured modal response and, therefore, decrease the tolerances of the test data for this first measured mode.

24. Accuracy of the finite element predictions for natural frequencies is very good as indicated in Table 16. Based on the prototype test results, the error in the finite element predictions ranged from less than one percent for modes 3 and 4 to 11.6 percent for mode 2. Finite element predictions were very sensitive to the inclusion of the foundation in the analysis. Comparisons of fixed-base predictions with those of the foundation indicate variations of 22-33 percent in the first four natural frequencies. Details of the finite element analysis

used for these predictions are presented in Reference 3.

Mode Shapes

25. Comparisons of mode shapes from analysis and model-prototype test results can be made from Plates 12, 13, and 14. In general, these comparisons are quite good. An important factor influencing mode shapes is the similarity in fixity at the abutments of the model and prototype. This boundary condition is difficult to model both physically and analytically. However, based on the results presented in Plates 12-14 fixity tends mainly to shift the node points along the crest with the effect being less for the lower modes.

Damping

26. Damping in the prototype ranged from 2.5 to 4.8 percent of critical with the lower value occurring in the third mode and the higher value in the fifth mode. Damping in the first asymmetric mode was measured at 4.3 percent. All damping calculations for the prototype dam were based on the bandwidth method, as previously discussed. Damping for the model was determined by the log decrement method with values ranging from 2 to 5 percent of critical. These damping ratios are consistent with expected values both for the model and prototype.

Hydrodynamic Pressures

27. Hydrodynamic pressures are presented as a function of excitation frequency and dam height in Plates 9 and 10. The increase in pressure near the top of the dam at sta 8 indicates the flexibility of the dam in this region. The correlation of pressure measurements made on the model when excited by a base force input and those predicted using Westergaard's theory are quite good (Reference 3).

28. The pressures measured in the prototype tests with those in the model tests for crest excitation can be observed in Plate 11.

The actual hydrodynamic pressures are presented in Plate 11 at two crest station locations and three frequencies of excitation. It should be mentioned that the model and prototype were excited at harmonic force levels that are not directly proportional to the appropriate scale factor; consequently, the measured pressures are not scaleable. Therefore, the pressures presented in Plate 11 should not be compared on the basis of absolute values but rather on similarities in the patterns of the model and prototype values over the normalized height of the dam. As discussed in Reference 3, the increase in pressures in the more flexible upper part of the dam is evident by observing Plate 11.

PART VI: CONCLUSIONS

29. Based on cost and accuracy of predictions, model tests are very attractive in studying vibration characteristics of dams. The first four natural frequencies determined from model tests were within 0.1-25 percent of those measured on the prototype. Also, model tests provide an effective means for studying the interaction of a dam with its reservoir and its foundation. Magnification of hydrodynamic pressures, as reported in Reference 3, due to dam flexibility should be considered in aseismic design of dams.

30. Linear finite element analyses can be very accurate in predicting vibration characteristics for concrete arch dams. Accuracy in the range of 0.5-11.6 percent, as indicated in Table 16, is exceptionally good for large complex structures such as arch dams. Also, finite element analyses are invaluable in providing a means for studying parameteric effects such as structure-foundation interaction and clustering of natural frequencies.

31. The model test results indicate that until a more sophisticated method for including hydrodynamic interaction is developed, Westergaard's procedure, rationally applied, provides reasonable results.

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Table 1

Frequency Response Data: Sta 6, Basket Load Empty, Vibrators out of Phase, Run 1

Frequency Hz	a 0.001 g's	A μin./kip-ft
5.33	3.24	1.73
5.42	3.67	1.82
5.50	4.36	2.04
5.58	5.17	2.29
5.67	6.13	2.54
5.75	7.24	2.84
5.83	7.28	2.70
5.92	6.55	2.29
6.00	5.85	1.94
6.08	5.15	1.62
6.17	4.44	1.31
6.25	3.50	0.98
6.33	3.05	0.82
6.42	2.38	0.60
6.50	2.49	0.60

Table 2

Frequency Response Data: Sta 6, Basket Load S1,

Vibrators out of Phase, Runs 2 and 3

Frequency Hz	a 0.001 g's	A μin./kip-ft
	Run 2	
5.17	4.71	1.55
5.25	5.37	1.66
5.33	6.15	1.80
5.42	7.2	1.97
5.50	8.7	2.24
5.58	10.38	2.52
5.67	12.50	2.85
5.70	13.28	2.96
5.73	14.03	3.07
5.77	14.2	3.02
5.80	13.85	2.89
5.83	13.85	2.82
5.87	13.55	2.69
5.90	13.01	2.55
5.92	12.85	2.46
5.93	12.85	2.45
5.97	12.3	2.28
6.00	11.8	2.15
6.08	10.4	1.79
6.08	10.55	1.82
6.25	8.8	1.36
6.33	6.8	1.0
6.42	6.63	0.92
6.50	5.98	0.79
	Run 3	
5.50	8.34	2.15
5.53	8.98	2.26
5.57	9.60	2.35
5.60	10.33	2.47
5.63	10.95	2.57
5.67	11.85	2.70
5.70	12.65	2.82
5.73	13.12	2.87
5.77	13.22	2.81
5.80	13.15	2.74

(Continued)

Table 2 (Concluded)

Frequency Hz	a 0.001 g's	A μin./kip-ft
	Run 3 (Continued)	
5.83	13.05	2.66
5.87	12.80	2.54
5.90	12.68	2.47
5.93	12.20	2.32
5.97	11.90	2.21
6.00	11.52	2.09
6.07	10.52	1.83
6.13	9.10	1.52
6.20	7.78	1.24
6.27	6.95	1.06

Table 3

Frequency Response Data: Sta 8, Basket Load S1, Vibrators in Phase, Runs 4 and 5

Frequency Hz	a 0.001 g's	A μin./kip
	Run 4	
6.00	3.66	166
6.07	4.31	187
6.13	4.96	207
6.20	5.61	224
6.23	6.0	235
6.27	6.58	251
6.30	6.81	255
6.33	6.73	247
6.37	6.18	221
6.37	6.22	223
6.40	5.37	189
6.47	4.35	146
6.53	3.51	114
6.60	3.01	93
	Run 5	
5.97	2.33	108
6.00	2.68	122
6.03	2.90	129
6.07	3.09	134
6.10	3.70	157
6.13	3.48	145
6.17	4.23	172
6.20	4.49	179
6.23	5.14	201
6.25	5.73	221
6.27	5.80	221
6.30	5.99	224
6.33	5.85	215
6.37	5.54	198
6.40	5.01	176
6.43	4.51	155

(Continued)

Table 3 (Concluded)

Frequency Hz	a 0.001 g's	A μin./kip
	Run 5 (Continued)	
6.47	4.04	136
6.50	3.67	121
6.53	3.40	110
6.57	3.17	100
6.60	2.96	92
6.63	2.85	87
6.67	2.69	80

Table 4

Frequency Response Data: Sta 6, Basket Load Empty, Vibrators out of Phase, Runs 6, 7, and 8

Frequency Hz	a 0.001 g's	A μin./kip-ft
	Run 6	
7.25	1.13	0.18
7.27	1.24	0.19
7.30	1.41	0.21
7.33	1.66	0.25
7.37	1.70	0.25
7.42	2.16	0.31
7.50	2.51	0.34
7.53	2.61	0.35
7.57	2.72	0.36
7.60	2.82	0.36
7.63	2.81	0.36
7.67	2.74	0.34
7.70	2.66	0.32
7.73	2.76	0.33
7.77	2.57	0.30
7.80	2.64	0.31
7.83	2.53	0.29
7.92	2.38	0.26
8.00	1.75	0.18
	Run 7	
7.17	2.26	0.37
7.20	2.57	0.41
7.23	2.76	0.43
7.27	3.18	0.49
7.30	3.35	0.51
7.33	3.62	0.54
7.37	3.98	0.58
7.40	4.15	0.59
7.42	4.15	0.59
7.43	4.35	0.61
7.47	4.61	0.64
7.50	5.02	0.68
7.53	5.05	0.67
7.57	5.32	0.70
7.58	5.32	0.69
7.60	5.14	0.66

(Continued)

Table 4 (Concluded)

Frequency Hz	a 0.001 g's	A μin./kip-ft
	Run 7 (Continued)	
7.63	5.61	0.71
7.67	5.13	0.64
7.75	4.84	0.58
7.83	4.48	0.51
7.92	4.07	0.44
8.00	4.12	0.43
	Run 8	
6.92	0.82	0.15
7.00	1.36	0.24
7.08	2.01	0.34
7.17	2.69	0.44
7.25	3.7	0.57
7.33	4.87	0.72
7.42	6.51	0.92
7.50	7.32	0.99
7.58	7.02	0.91
7.67	6.49	0.80
7.75	6.02	0.72
7.83	5.5	0.68
7.92	5.57	0.61
8.00	4.89	0.51

Table 5

Frequency Response Data: Sta 8, Vibrators in Phase,

Runs 9 and 10

Frequency Hz	a 0.001 g's	A μin./kip
	Run 9, Basket Load S1	
8.20	8.85	90
8.27	9.73	96
8.33	10.88	104
8.40	11.73	109
8.47	12.20	109
8.50	12.40	110
8.53	12.33	107
8.57	12.28	105
8.60	12.35	104
8.63	12.20	101
8.67	11.88	97
8.73	11.55	92
8.80	11.30	87
8.87	11.20	83
8.93	10.65	77
9.00	10.35	73
	Run 10, Basket Load Empty	
7.87	4.65	56
7.93	5.46	64
8.00	6.51	73
8.07	7.78	85
8.13	9.05	96
8.20	10.28	105
8.27	11.45	113
8.33	12.18	117
8.40	12.78	118
8.47	12.83	115
8.53	12.70	111
8.60	12.25	103
8.67	11.78	96
8.73	11.50	91
8.80	11.18	86
8.87	10.90	81
8.93	10.63	77
9.00	10.48	74

Table 6

Summary of Crest Mode Shape Data

f = 5.80 Hz

	Relative Amplitude for Run No.							
	9/25/74		9/30/74		10/1/74		10/2/74	
Sta	2	3	5	6	12	13	16	Avg.
1R		0	0					0
1T								0
2R		0	0					0
2T		-0.01						-0.01
3R		-0.02	-0.02	-0.01			-0.02	-0.02
3T		-0.01					-0.01	-0.01
3-1/2R			±0.02	±0.02				±0.02
3-1/2T								--
4R		0.08	0.08	0.07			0.08	0.08
4T		-0.03					-0.03	-0.03
4-1/2R							0.24	0.24
4-1/2T							-0.02	-0.02
5R	0.50			0.49		0.51	0.53	0.52
5T	-0.02					-0.03	±0.02	-0.02
5-1/2R					0.75	0.76		0.76
5-1/2T						0.06		0.06
6R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6T	0.09	0.11		0.12	0.11	0.08	0.08	0.10
6-1/2R					0.83			0.83
6-1/2T								--
7R	0.55				0.57	0.59		0.59
7T	0.15					0.13		0.14
7-1/2R					0.12			0.12
7-1/2T								--
8R	-0.39	-0.41	-0.35	-0.34	-0.39	-0.40	-0.37	-0.38
8T	0.17	0.18	0.11	0.15	0.15	0.16	0.15	0.16
8-1/2R							-0.69	-0.69
8-1/2T							0.12	0.12
9R	-0.85					-0.88		-0.87
9T	0.14					0.04		0.09
10R	-0.59	-0.62				-0.52	-0.60	-0.60
10T	-0.05	0.01				±0.02	0.02	0.03
11R	-0.14					-0.14		-0.14
11T	-0.02					-0.03		-0.03
12R	0.01							0.01
12T	-0.01							-0.01
13R		0						0
13T								

Table 7

Summary of Crest Mode Shape Data

f = 6.30 Hz

	Relative Amplitude for Run No.							
	9/25/74		9/30/74			10/1/74	10/2/74	
Sta	2	3	5	6	7	13	16	Avg.
1R		0	0					0
1T		0						0
2R		0	0					0
2T		0						0
3R		-0.05	±0.05	±0.05			±0.06	±0.06
3T		±0.01					-0.02	-0.02
3-1/2R			±0.20	0.18				0.19
3-1/2T								--
4R		±0.24	±0.41	±0.33			±0.39	±0.34
4T		±0.04					±0.03	±0.03
4-1/2R							--	--
4-1/2T							0.06	0.06
5R	0.85			0.76		0.69	0.84	0.79
5T	0.08					0.07	0.08	0.08
5-1/2R						0.97		0.97
5-1/2T						0.10		0.10
6R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6T	0.20	0.11		0.16		0.10	0.15	0.15
6-1/2R								--
6-1/2T								--
7R	-0.90					-0.72		-0.81
7T	0.15					0.11		0.13
7-1/2R					-1.62			-1.62
7-1/2T								--
8R	-1.35	±1.04	-1.44	-1.29		±1.00	±1.34	±1.24
8T	-0.18	0.12	-0.25	-0.10		±0.15	±0.17	±0.16
8-1/2R							±1.25	±1.25
8-1/2T							±0.19	±0.19
9R	1.55					1.44		1.50
9T	-0.18					-0.11		-0.15
10R	2.41	1.81				2.28	2.56	2.27
10T	-0.08	-0.05				-0.07	-0.07	-0.07
11R	0.80					0.71		0.76
11T	0.13					±0.12		±0.13
12R	0.04							0.04
12T	±0.04							±0.04
13R		0						0
13T		0						0

Table 8

Summary of Crest Mode Shape Data

f = 7.63 Hz

	Relative Amplitude for Run No.							
	9/25/74		9/30/74		10/1/74		10/2/74	
Sta	2	3	5	6	12	13	16	Avg.
1R		0	0					0
1T		--						--
2R		0	0					0
2T		--						--
3R		0.05	-0.05	0.04			0.04	0.05
3T		-0.03					-0.01	-0.02
3-1/2R			±0.13	0.10				0.12
3-1/2T								--
4R		0.49	0.27	0.24			0.86	0.47
4T		-0.05					-0.03	-0.04
4-1/2R							0.59	0.59
4-1/2T							±0.05	±0.05
5R	±0.64			0.83		0.64	0.99	0.78
5T	-0.03					±0.03	±0.06	±0.04
5-1/2R					1.33	1.54		1.44
5-1/2T						0.14		0.14
6R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6T	0.10	0.06		0.08	0.10	0.10	0.05	0.08
6-1/2R					-1.63			-1.63
6-1/2T								
7R	±1.61				-2.06	±2.27		±1.98
7T	0.19					-0.12		-0.16
7-1/2R					-0.99			
7-1/2T								
8R	±0.50	±0.59	±0.61	±0.59	±0.66	0.77	0.73	0.64
8T	0.25	-0.32	0.28	0.29	±0.29	-0.32	-0.32	-0.30
8-1/2R							±2.09	±2.09
8-1/2T							-0.20	-0.20
9R	±1.04					±1.20		±1.12
9T	0.10					0.09		0.10
10R	2.35	-1.48				±3.64	±3.17	±2.66
10T	0.06	0.05				0.14	0.20	0.11
11R	±1.27					±1.98		±1.63
11T	0.14					0.18		0.16
12R	±0.11							±0.11
12T	0.07							0.07
13R		0						
13T		--						

Table 9

Summary of Crest Mode Shape Data

f = 8.53 Hz

	Relative Amplitude for Run No.							
	9/25/74	9/30/74			10/1/74		10/2/74	
Sta	2	5	6	7	10	13	16	Avg.
1R		0						0
1T								--
2R		0						0
2T								--
3R		-0.23	-0.23				-0.24	-0.23
3T							-0.04	-0.04
3-1/2R		-0.66	-0.66					-0.66
3-1/2T								--
4R		-1.00	-0.98				-1.01	-1.00
4T							-0.03	-0.03
4-1/2R							-1.15	-1.15
4-1/2T							±0.09	±0.09
5R	±0.81	±0.75				±0.82	-0.69	±0.77
5T	0.13					0.13	±0.13	0.13
5-1/2R					0.52	0.60		0.56
5-1/2T						0.13		0.13
6R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6T	0.07		±0.05		±0.06	0.07	0.06	0.07
6-1/2R					1.10			1.10
6-1/2T								--
7R	0.53				0.54	0.56		0.54
7T	-0.09					0.05		0.07
7-1/2R				-0.35				-0.35
7-1/2T								--
8R	-0.81	-0.70	-0.74		-0.78	-0.77	-0.81	-0.77
8T	-0.01	-0.07	-0.02		0	-0.02	0.01	-0.03
8-1/2R							-0.62	-0.62
8-1/2T							±0.07	±0.07
9R	0.29					0.30		0.30
9T	0.12					±0.11		0.12
10R	1.78					1.63	1.85	1.75
10T	0.04					0.10	±0.07	0.07
11R	0.92					0.90		0.91
11T	-0.08					±0.08		±0.08
12R	0.10							0.10
12T	-0.05							-0.05
13R								0
13T								0

Table 10

Summary of Cantilever Mode Shape Data

Sta 6

Location	f = 5.80 Hz Adjusted	f = 5.80 Hz Normal	f = 6.30 Hz Adjusted	f = 6.30 Hz Normal	f = 7.62 Hz Adjusted	f = 7.62 Hz Normal	f = 8.53 Hz Adjusted	f = 8.53 Hz Normal
6CR	0.28	0.28	0.05	0.05	±0.44	±0.44	0.29	0.29
6AR	0.02	0.02	0.02	0.02	-0.031	-0.031	0.01	0.01
6CT	0.04	0.04	±0.09	±0.09	0.09	0.09	-0.04	-0.04
6DR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6AT	-0.01	-0.01	±0.02	±0.02	0.03	0.03	-0.01	-0.01
6DT	0.04	0.04	0.13	0.13	0.12	0.12	±0.05	±0.05
6BR	0.04	0.04	-0.02	-0.02	-0.08	-0.08	-0.03	-0.03
6BT	-0.02	-0.02	0.02	0.02	0.06	0.06	0.02	0.02

Table 11

Summary of Cantilever Mode Shape Data

Sta 8

Location	f = 5.80 Hz Adjusted	f = 5.80 Hz Normal	f = 6.30 Hz Adjusted	f = 6.30 Hz Normal	f = 7.62 Hz Adjusted	f = 7.62 Hz Normal	f = 8.53 Hz Adjusted	f = 8.53 Hz Normal
8DR	-0.38	1.00	-1.08	1.00	0.69	1.00	-0.79	1.00
8AR	-0.02	0.05	±0.04	±0.04	0.04	0.06	-0.02	0.03
8BR	-0.07	0.18	-0.18	0.17	0.10	0.14	-0.09	0.10
6DR	1.00	-2.63	1.00	-0.93	1.00	1.44	1.00	-1.27
8AT	0.01	-0.03	0	0	-0.05	-0.07	0	0
8BT	0.08	-0.21	-0.05	0.05	-0.20	-0.29	0.01	-0.01
8CR	-0.18	0.47	±0.20	±0.19	0.22	0.32	-0.22	0.28
8CT	0.14	-0.37	-0.11	0.10	-0.37	-0.54	0.03	-0.04
8DT	0.14	-0.37	-0.10	0.09	-0.27	-0.39	-0.05	0.06

Table 12

Summary of Cantilever Mode Shape Data

Sta 10

Location	f = 5.80 Hz		f = 6.30 Hz		f = 7.62 Hz		f = 8.53 Hz	
	Adjusted	Normal	Adjusted	Normal	Adjusted	Normal	Adjusted	Normal
8DR	-0.39	0.62	-1.23	-0.67	±0.95	0.24	-0.76	-0.46
10BR	-0.01	0.02	-0.01	-0.01	0.01	0	0.01	0.01
10DR	-0.63	1.00	1.83	1.00	±3.93	1.00	1.66	1.00
6DR	1.00	-1.59	1.00	0.55	1.00	±0.25	1.00	0.60
10BT	-0.01	0.02	0.02	0.01	0.01	0	±0.01	±0.01
10CT	-0.04	0.06	±0.06	±0.03	±0.09	0.02	0.02	0.01
10CR	-0.14	0.22	0.03	0.02	±0.07	0.02	0.27	0.16
10DT	±0.03	±0.05	-0.08	-0.04	±0.26	0.07	-0.18	-0.11

Table 13

Hydrodynamic Pressure Data

Sta 6

Depth Below Crest of Dam ft	Pressure, psi			
	Out of Phase		In Phase	
	f = 5.80 Hz	f = 7.62 Hz	f = 6.30 Hz	f = 8.53 Hz
100	0.06	0.03	0.006	0.05
90	0.06	0.02	0.006	0.04
80	0.06	0.02	0.006	0.04
70	0.06	0.02	0.006	0.04
60	0.06	0.02	0.006	0.04
50	0.07	0.02	0.007	0.05
40	0.07	0.02	0.011	0.06
30	0.07	0.02	0.010	0.06
20	0.07	0.02	0.012	0.05
10	0.06	0.01	0.012	0.07
6 in. below water surface	0.01	0.00	0.002	0.06

Table 14

Hydrodynamic Pressure Data

Sta 8

Depth Below Crest of Dam ft	Pressure, psi			
	Out of Phase		In Phase	
	f = 5.80 Hz	f = 7.62 Hz	f = 6.30 Hz	f = 8.53 Hz
100	0.012	0.003	0.003	0.006
80	0.014	0.005	0.011	0.012
60	0.022	0.002	0.020	0.021
40	0.028	0.004	0.025	0.032
20	0.027	0.006	0.026	0.040
8 in. below water surface	0.006	0.002	0.005	0.008

Table 15

Hydrodynamic Pressure Data

Sta 10

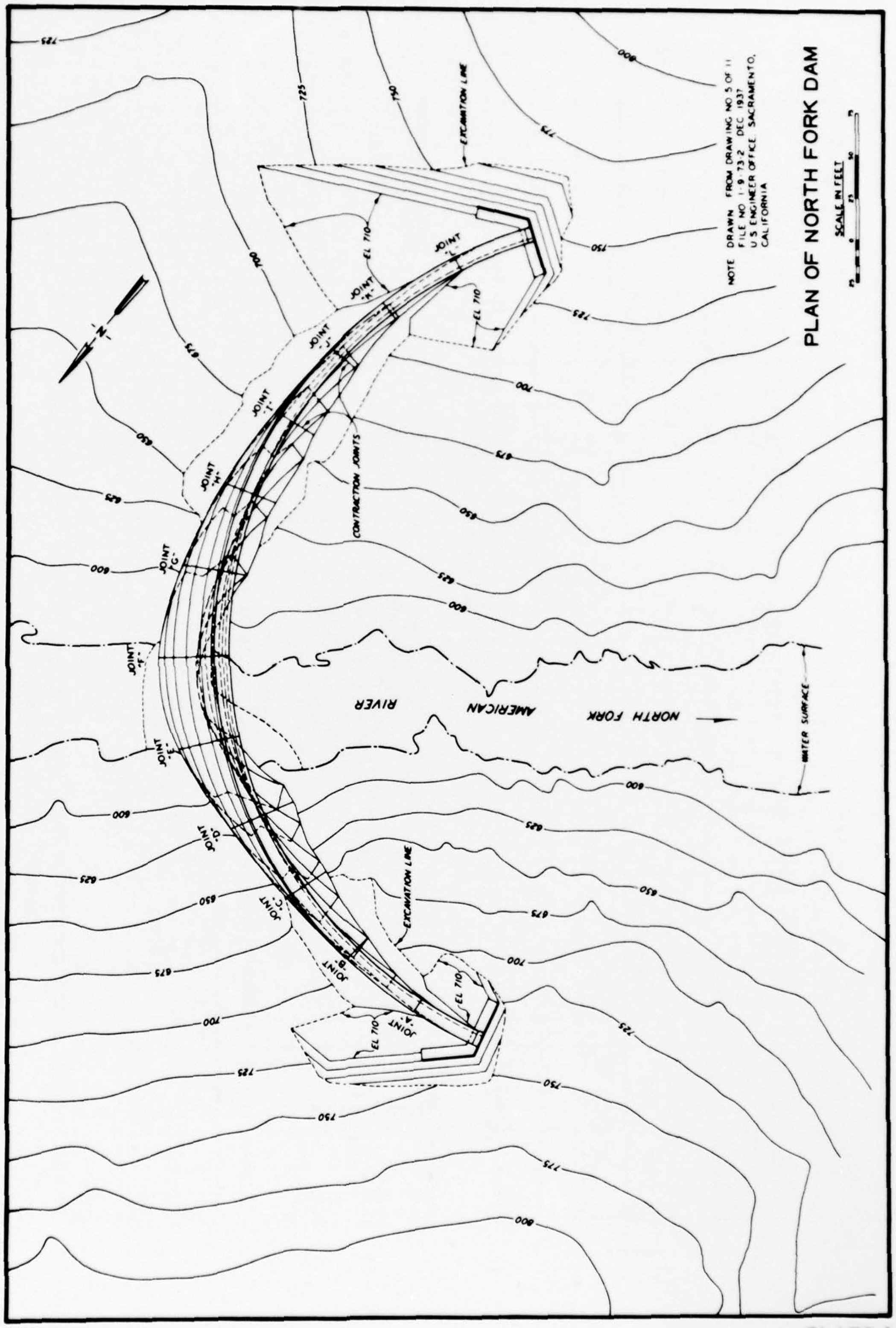
Depth Below Crest of Dam ft	Pressure, psi			
	Out of Phase		In Phase	
	f = 5.80 Hz	f = 7.62 Hz	f = 6.30 Hz	f = 8.53 Hz
60	0.048	0.002	0.029	0.008
40	0.048	0.002	0.032	0.090
20	0.048	0.006	0.036	0.092
8 in. below water surface	0.007	0.004	0.008	0.016

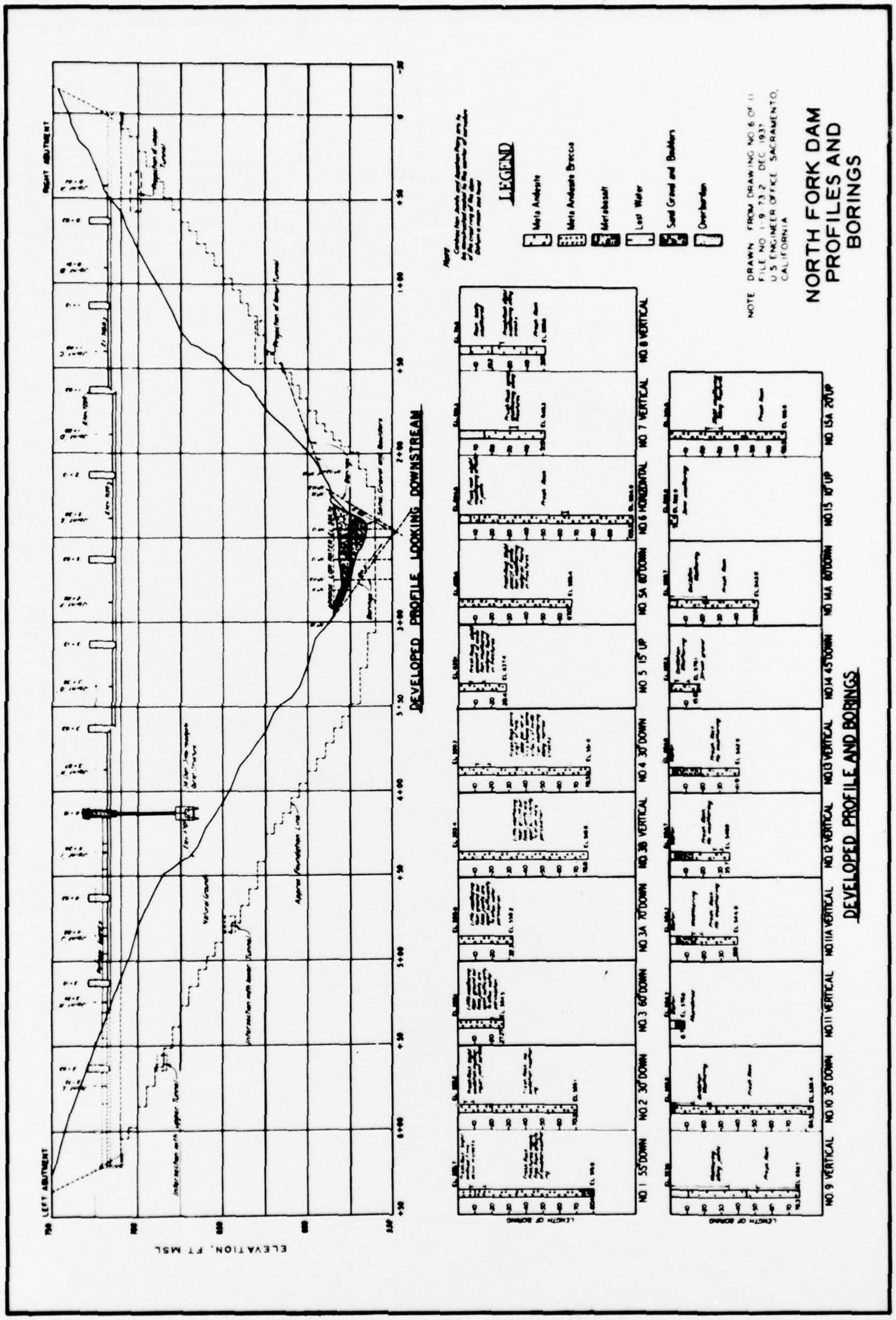
Table 16

Comparison of Natural Frequencies for

Analytical, Model, and Prototype Dam

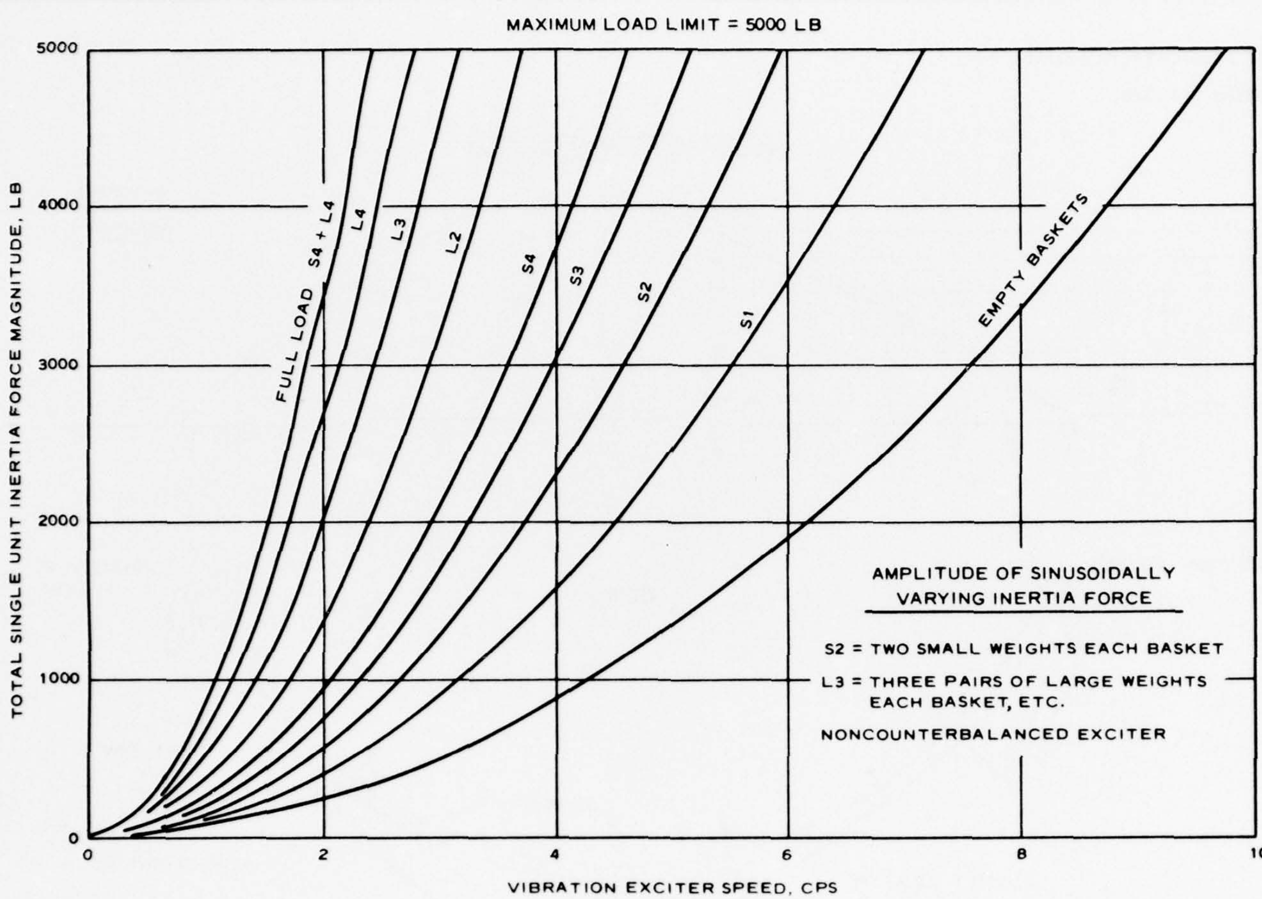
Mode	Reservoir Condition	Natural Frequency, Hz		
		Analytical	Model	Prototype
1	Full	5.17	--	--
1	Empty	6.67	--	--
2	Full	5.08	4.29	5.75
2	Empty	6.75	5.54	--
3	Full	6.29	6.12	6.30
3	Empty	8.17	6.29	--
4	Full	7.58	7.29	7.54
4	Empty	9.62	8.88	--
5	Full	--	10.12	8.40
5	Empty	--	12.38	--


PLAN OF NORTH FORK DAM
NOTE DRAWN FROM DRAWING NO 5 OF 11
FILE NO 1-9-73-2 DEC 1937
U S ENGINEER OFFICE SACRAMENTO, CALIFORNIA
SCALE IN FEET
NORTH FORK AMERICAN RIVER
WATER SURFACE
CONTRACTION JOINTS
EXCAVATION LINE
N

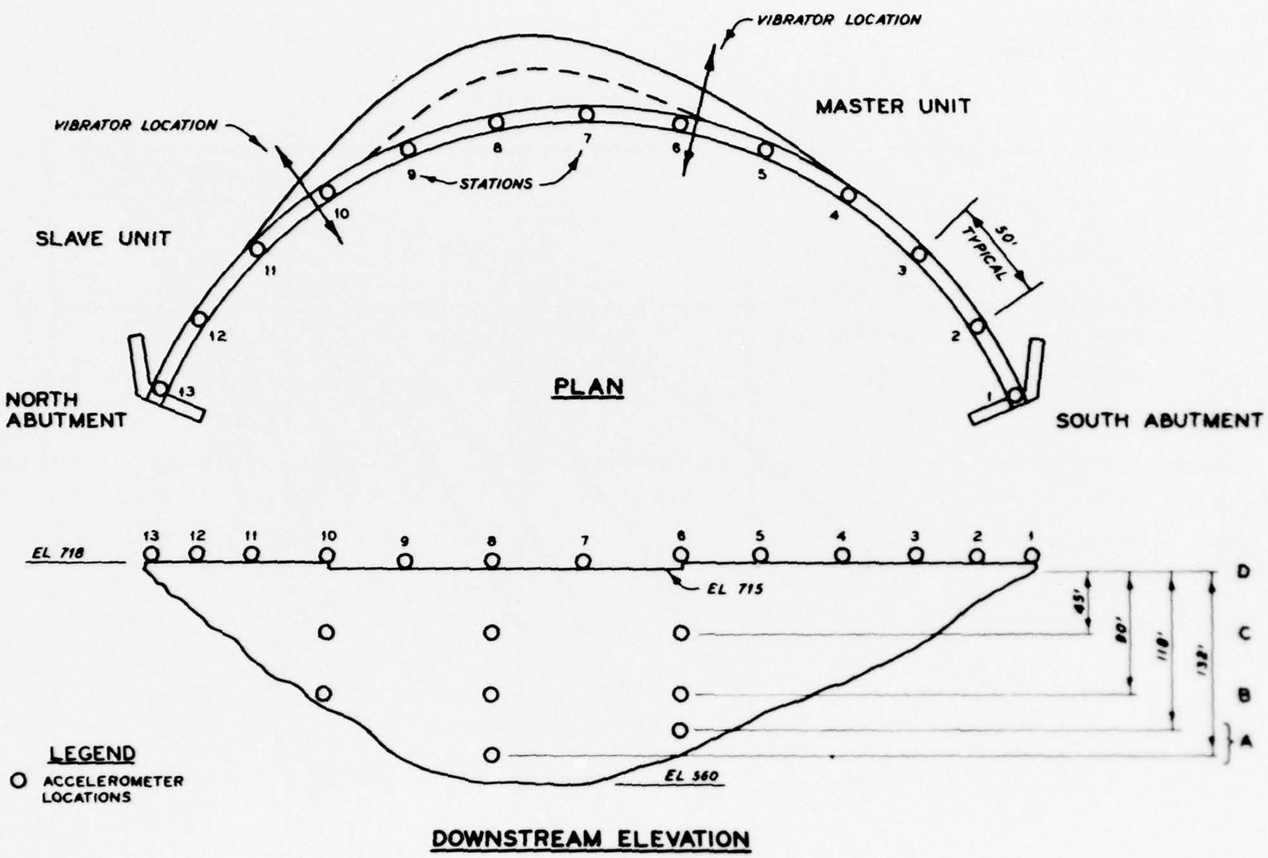


NORTH FORK DAM
PROFILES AND
BORINGS
NOTE DRAWN FROM DRAWING NO 6 OF 11 FILE NO 1-9-73 2 DEC 1937 U S ENGINEER OFFICE SACRAMENTO, CALIFORNIA
DEVELOPED PROFILE LOOKING DOWNSTREAM
DEVELOPED PROFILE AND BORINGS
LEGEND
Meta Andesite
Meta Andesite Breccia
Metabasalt
Lost Water
Sand Gravel and Boulders
Overburden
ELEVATION, FT MSL
LEFT ABUTMENT
RIGHT ABUTMENT
LENGTH OF BORING
NO 1 55° DOWN
NO 2 30° DOWN
NO 3 60° DOWN
NO 3A 70° DOWN
NO 3B VERTICAL
NO 4 30° DOWN
NO 5 15° UP
NO 5A 60° DOWN
NO 6 HORIZONTAL
NO 7 VERTICAL
NO 8 VERTICAL
NO 9 VERTICAL
NO 10 35° DOWN
NO 11 VERTICAL
NO 11A VERTICAL
NO 12 VERTICAL
NO 13 VERTICAL
NO 14 45° DOWN
NO 14A 60° DOWN
NO 15 10° UP
NO 15A 20° UP

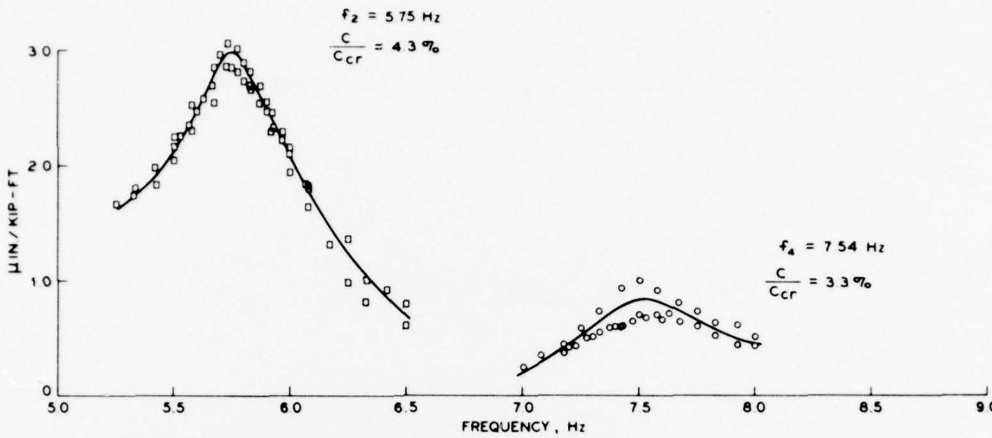
PLATE 2



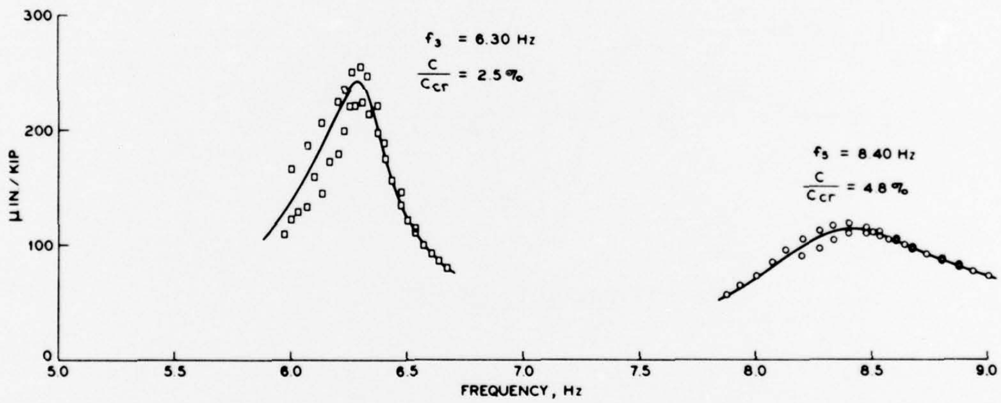
**VIBRATION FORCE OUTPUT VS SPEED–
NONCOUNTERBALANCED
(AFTER HUDSON[5])**



NORTH FORK DAM
INSTRUMENTATION LAYOUT

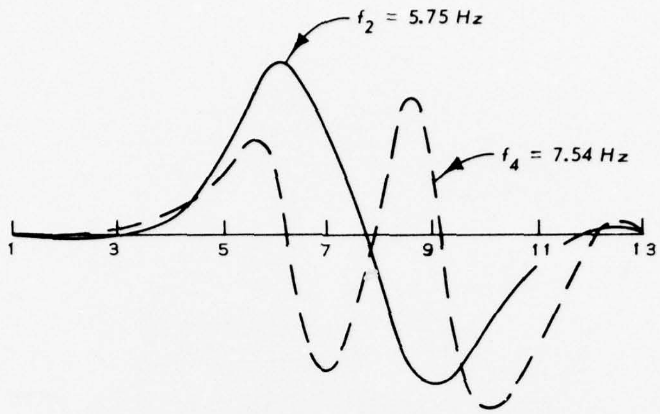


ASYMMETRICAL MODES

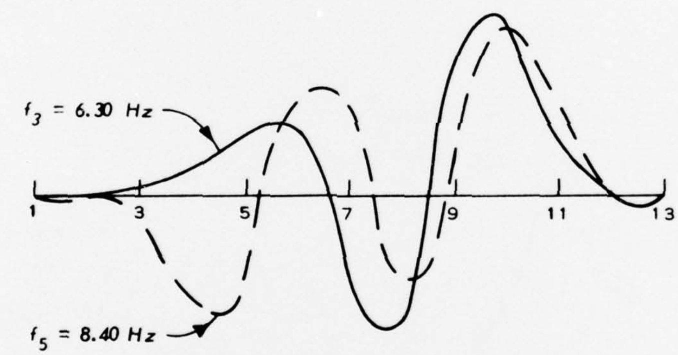


SYMMETRICAL MODES

FREQUENCY RESPONSE CURVES



ASYMMETRICAL MODE SHAPES

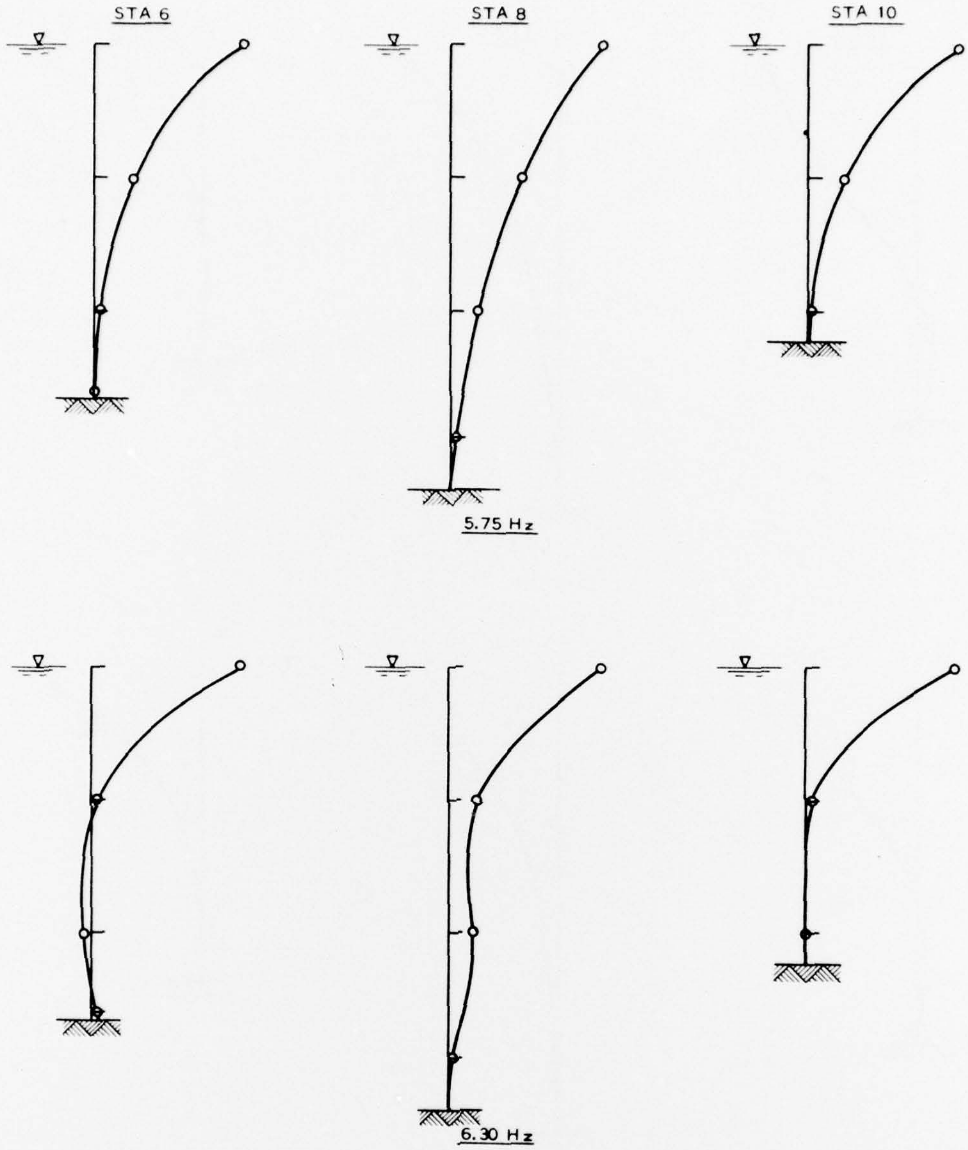


SYMMETRICAL MODE SHAPES

PROTOTYPE MODE SHAPES

RADIAL CREST DEFLECTIONS

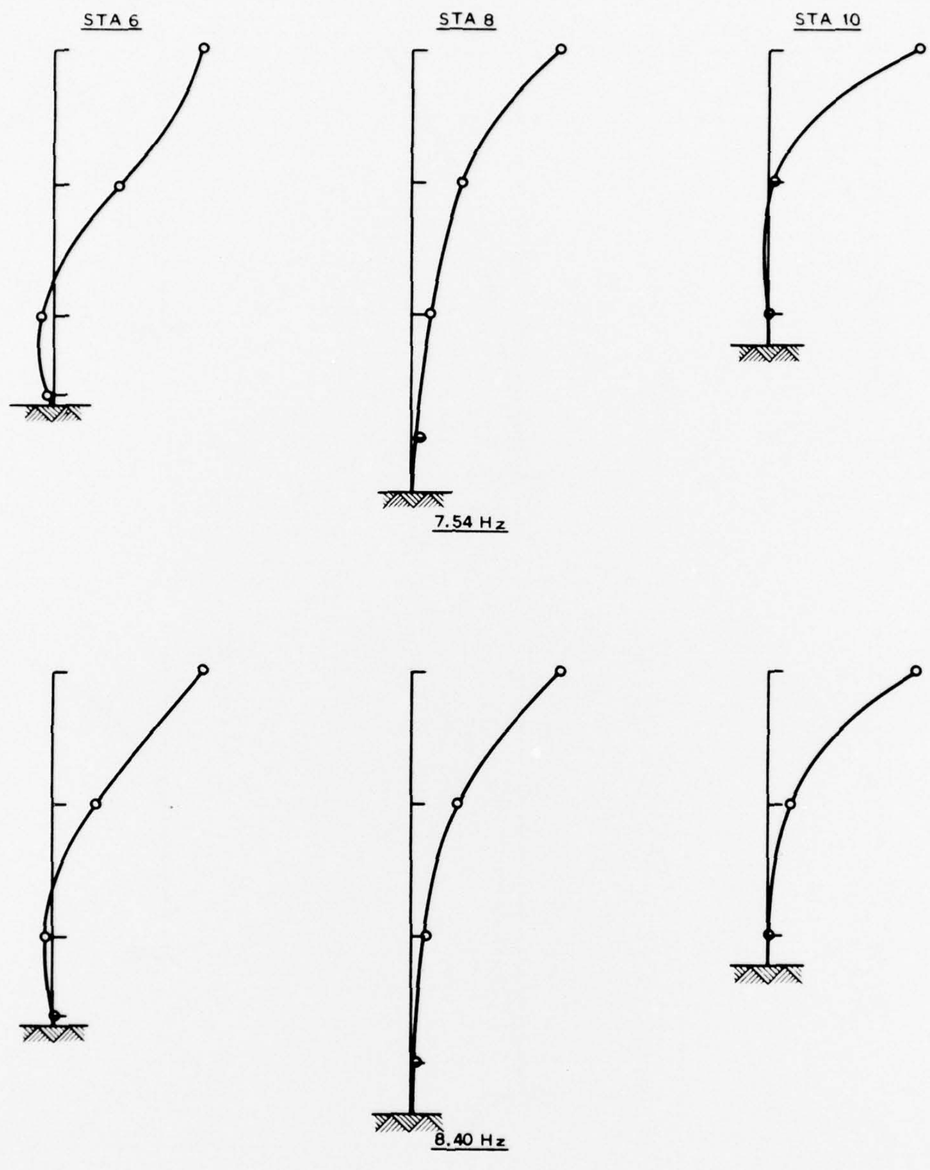
PLATE 6



PROTOTYPE MODE SHAPES

RADIAL CANTILEVER DEFLECTIONS
5.75 Hz AND 6.30 Hz

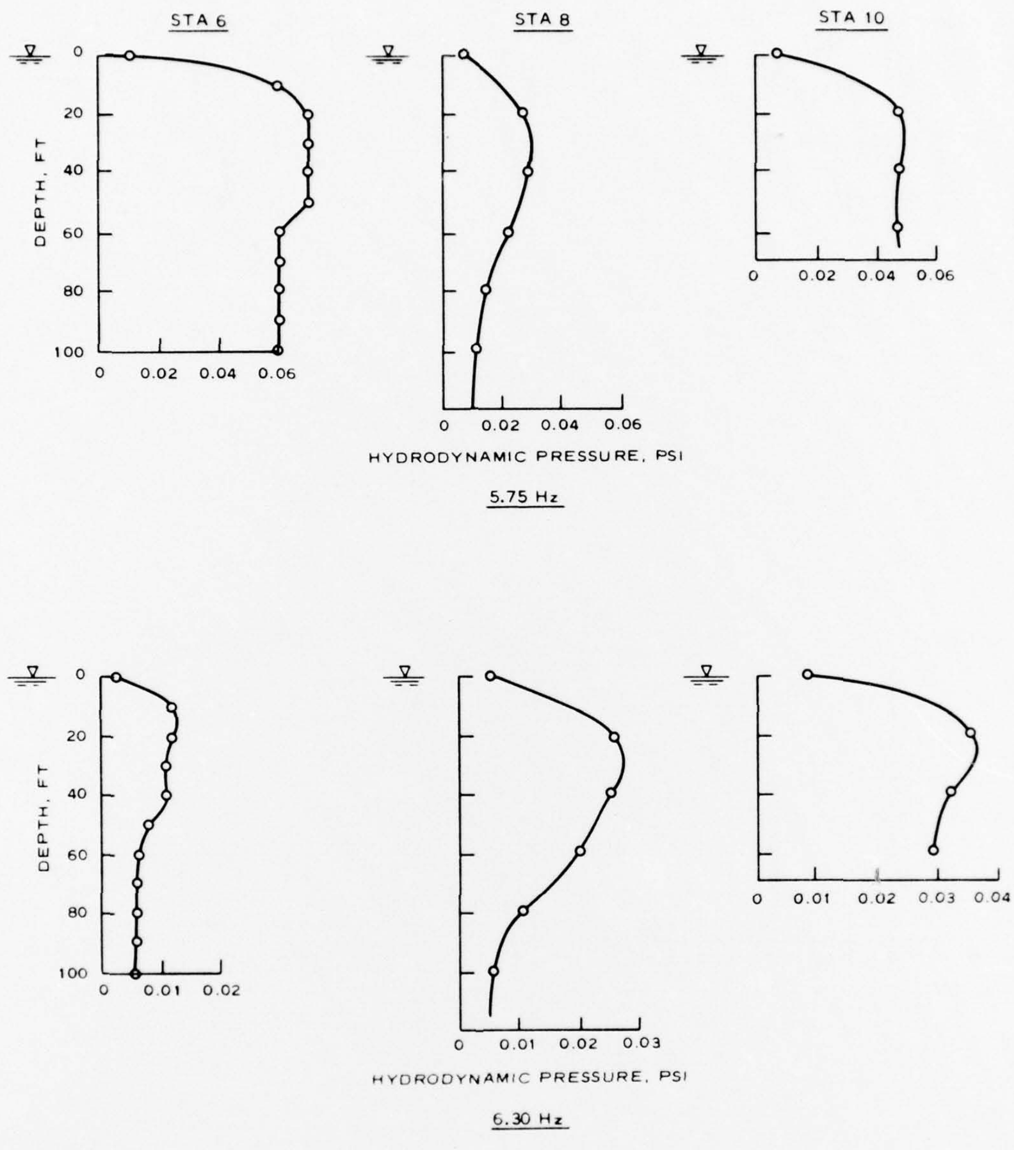
PLATE 7



PROTOTYPE MODE SHAPES

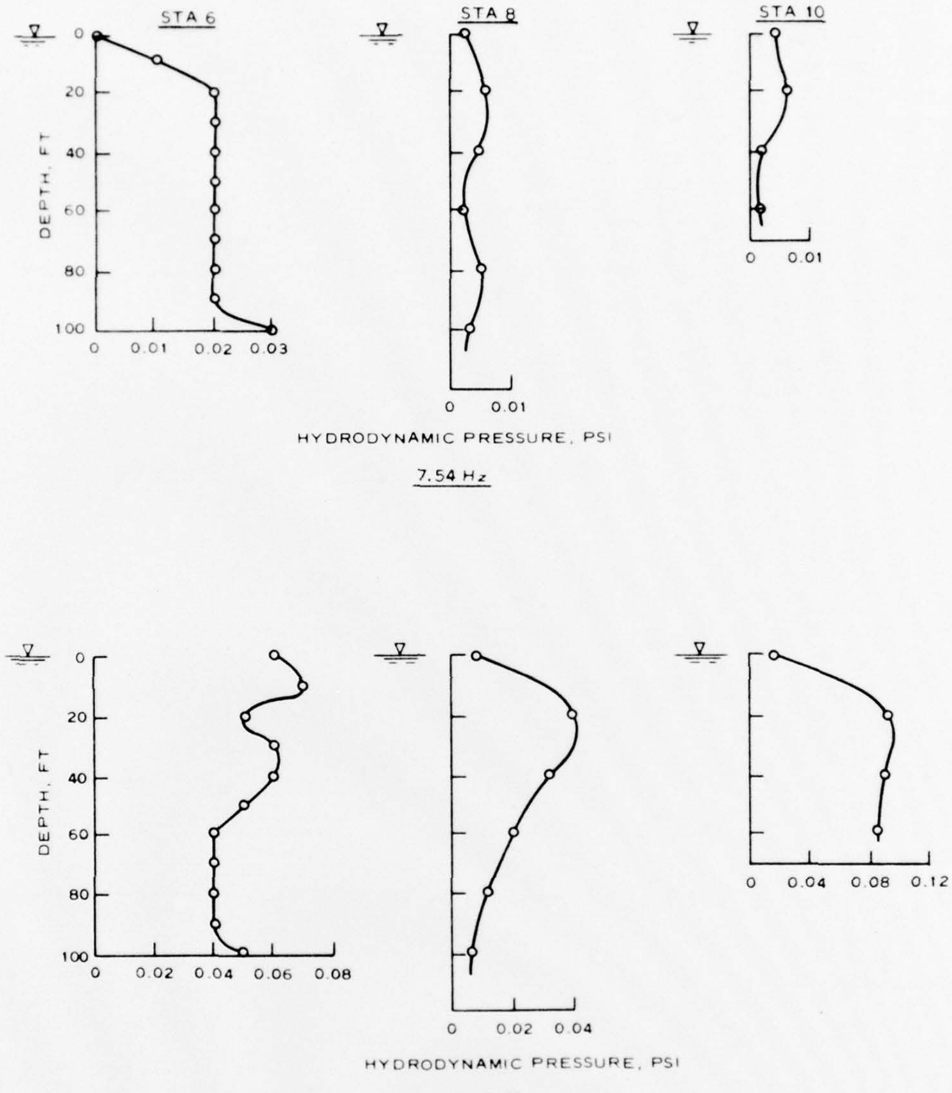
RADIAL CANTILEVER DEFLECTIONS
7.54 Hz AND 8.40 Hz

PLATE 8



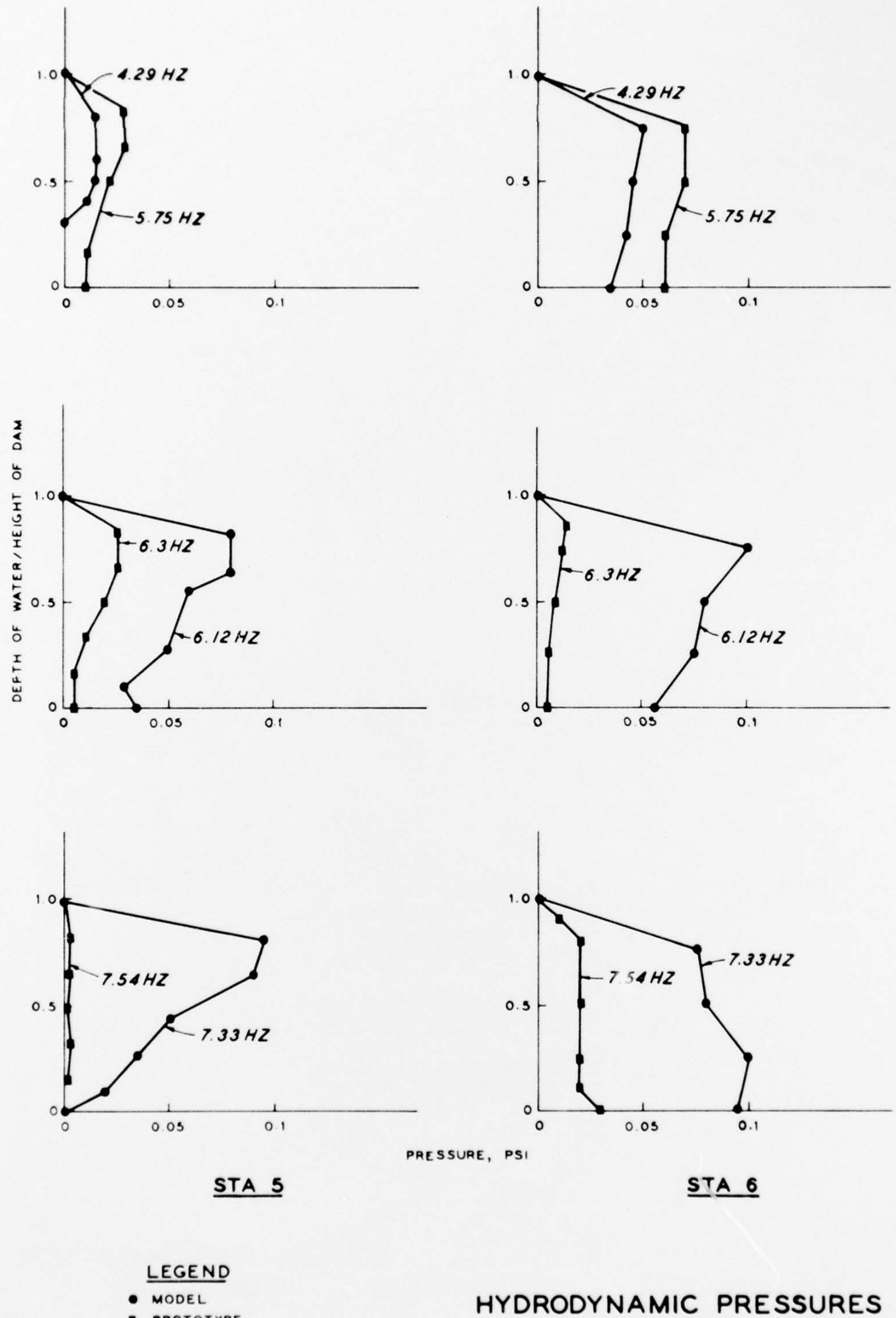
HYDRODYNAMIC PRESSURE VERSUS DEPTH

5.75 Hz AND 6.30 Hz

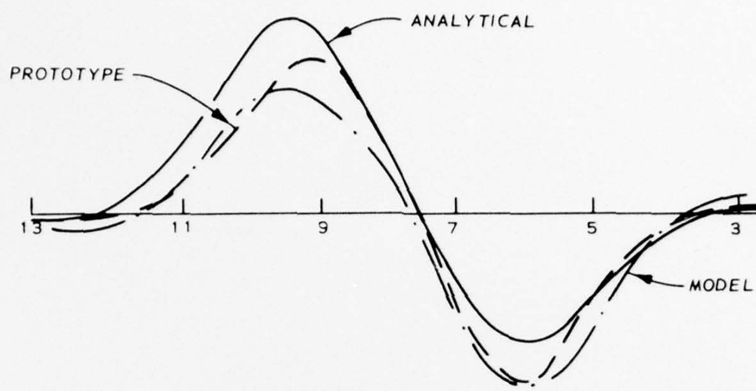


HYDRODYNAMIC PRESSURE VERSUS DEPTH

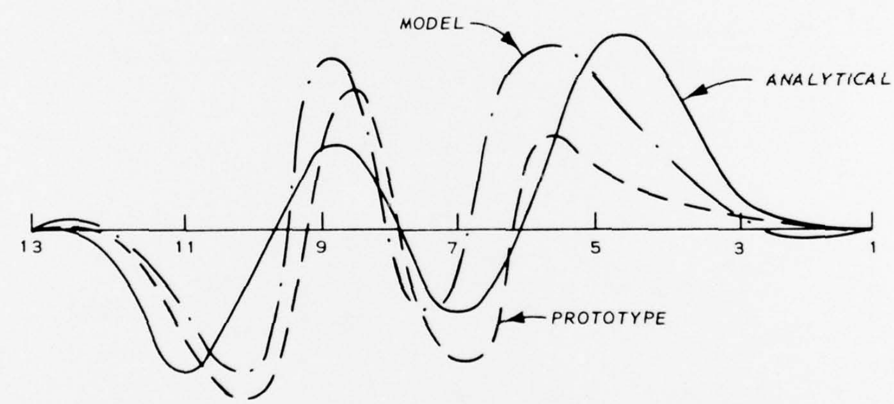
7.54 Hz AND 8.40 Hz



HYDRODYNAMIC PRESSURES
MODEL AND PROTOTYPE



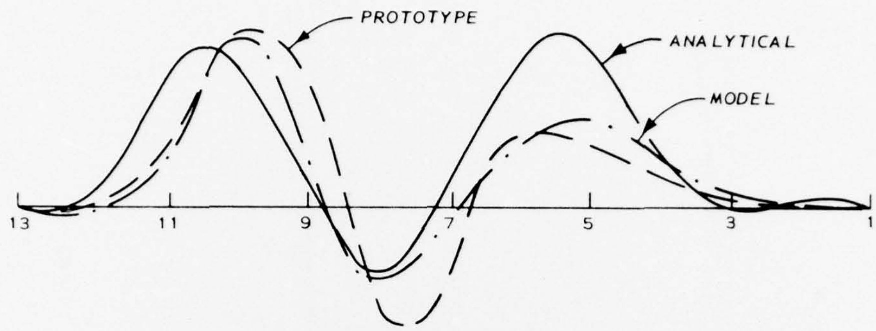
1ST ASYMMETRICAL MODE



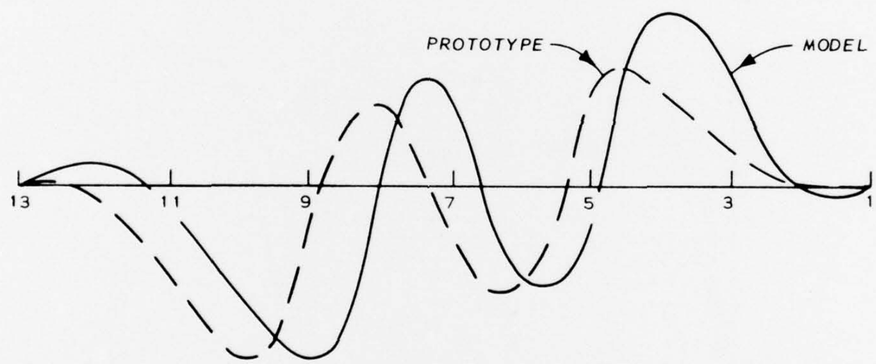
2ND ASYMMETRICAL MODE

COMPARISON OF ASYMMETRICAL MODE SHAPES

RADIAL CREST DEFLECTIONS



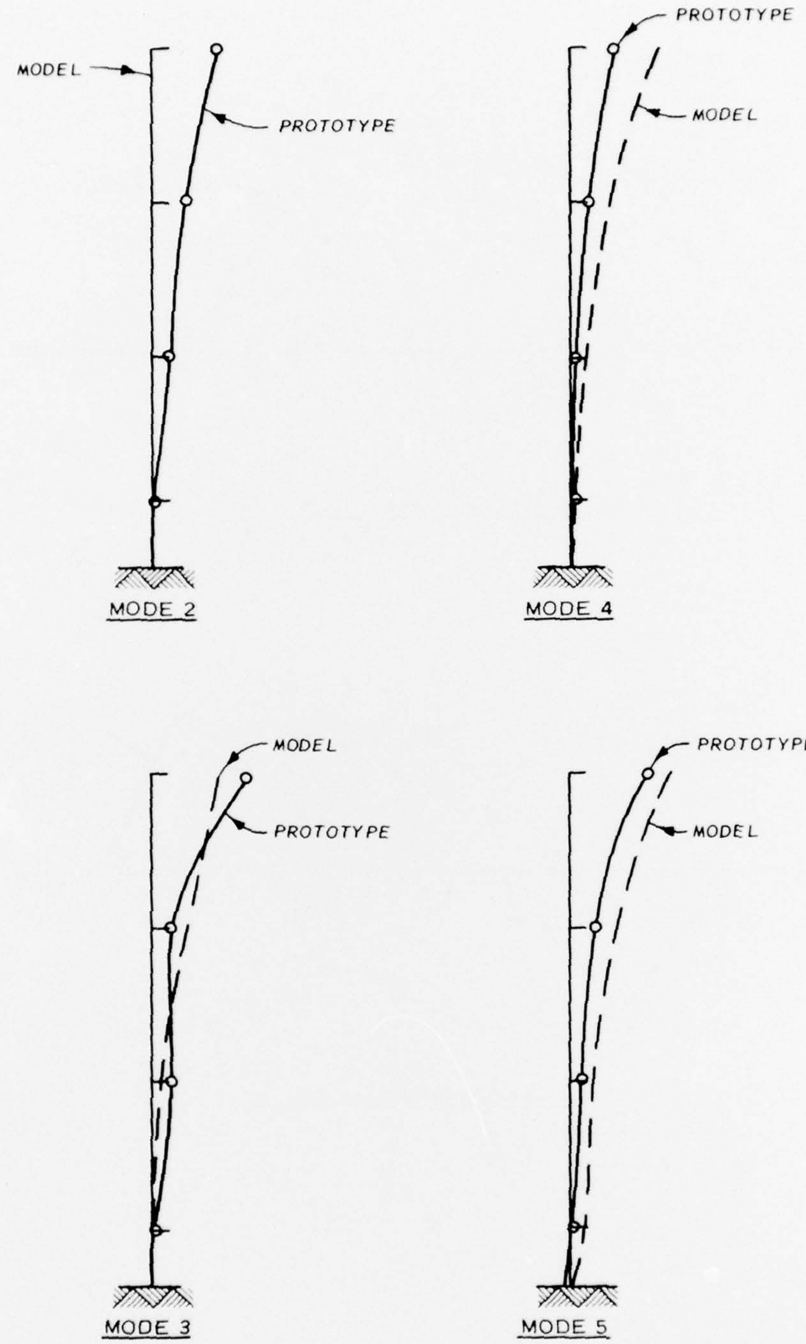
2ND SYMMETRICAL MODE



3RD SYMMETRICAL MODE

COMPARISON OF SYMMETRICAL MODE SHAPES

RADIAL CREST DEFLECTIONS



COMPARISON OF MODEL AND PROTOTYPE MODE SHAPES

RADIAL CANTILEVER DEFLECTIONS AT STA 8

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Crowson, Roger D
Comparison of vibration test results for a model and prototype arch dam, by Roger D. Crowson [and] Charles D. Norman. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report N-77-1)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Work Unit No. 31210.
Includes bibliography.

1. Arch dam. 2. Dynamic characteristics. 3. Dynamic tests. 4. Hydrodynamic pressures. 5. Models. 6. North Fork Dam. 7. Vibration tests. I. Norman, Charles D., joint author. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report N-77-1)
TA7.W34 no.N-77-1